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Studies of the availability of soil phosphorus (P) and potassium (K) in organic farming systems, and of plant adaptations to low P- and K-availability

DOCTOR SCIENTIARUM THESIS 2003:29

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Undersøkelser av tilgjengeligheten av P og K i jorda i økologiske dyrkingssystemer, og av planters tilpasning til lav tilgjengelighet av disse næringsstoffene

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ABSTRACT

In organic farming systems, the purchase of nutrients is firmly restricted as compared to conventional farming systems. This will often cause a negative nutrient budget on the field level, especially in cases with low animal density, where more nutrients are removed in yields than are applied in fertilisers. Studies on five organic dairy farms in Southern Norway, that were aiming at self-sufficiency, revealed that the concentrations of ammonium-acetate lactate (AL) soluble phosphorus (P) had decreased with time. The farms had been organically managed since 1986 or earlier. It was found that the higher the initial P-AL concentration, the greater was the decrease that occurred, calculated per year. Out of 156 topsoil samples, only 6 had low P-AL values (< 25 mg P kg^{-1} soil) at the second soil sampling. Nevertheless, in the long run, a supply of P will be required in organic farming systems. For potassium (K), no corresponding decrease in K-AL was found, but for this nutrient a considerable proportion of the cultivated land had low concentrations (< 65 mg K kg^{-1} soil) on all farms. The concentrations of acid-soluble K were also low to medium. With soil that does not have a high ability to replace K taken up by plants, a supply of K will be required in organic farming systems. Hence, the development of nutrient supplies that may fulfil the standards of organic farming is very important. Furthermore, organic farmers must strive even harder than their conventional colleagues to reduce nutrient losses caused by for example erosion or during animal manure storage and spreading.

A basic principle in organic farming is the cycling of nutrients within the farming system. With low animal density, plant material may be used as manure (green manure or mulching). The fate of P, K and nitrogen (N) was studied when chopped plant material was used as a mulch in vegetable growing. Application of 9-10 tonnes plant dry matter (DM) ha^{-1} increased vegetable yields by 26% in the year of application, and grain yields were increased by 0.6 tonne ha^{-1} in the subsequent year. However, when the nutrient uptake in non-mulched plants was subtracted, only 15-20% of the N, P and K applied in mulch was recovered by the vegetable crops.

Much of the N was probably lost by leaching or gaseous losses, whereas most of the surplus P and K were recovered in soil. The mulch-method is suited for relatively small farms with low animal density where there is no capacity to use all the farmland for vegetables. About 2/3 of the land should be used for mulch production, and 1/3 devoted to vegetables. A systematic crop rotation must be used to avoid an uneven distribution of nutrients within the farm.

Studies in low-P growing media have shown that plants may react to low P supply by adaptations such as increased root-shoot ratio, relatively longer and thinner roots or longer root hairs. Plants have a remarkable ability to adapt to changes in environmental conditions, such as a variable nutrient supply. In order to assess whether such adaptations might be useful for organic farming systems, this topic was studied by growing accessions of spring wheat and barley released during the period 1900-2000, in the field at both optimum and limited nutrient supply, as well as in the laboratory in low-P nutrient solution, where root traits were recorded. Nutrient uptake and grain yields varied significantly, but the relations between nutrient uptake and root traits were weak. Modern accessions produced higher yields than older ones, mostly because they had a higher harvest index and were more resistant to fungal disease. In cereal breeding, root traits should be recorded and the root length is important. As no significant differences in SRL were found among barley or wheat accessions in our study, I suggest that root characterisation may be simplified by estimating root length from the root weight and an appropriate value for the specific root length (SRL, m root g^{-1} root DM). Measuring SRL is very tedious.

Most studies that have shown large effects in root or root hair growth, as a consequence of low P supply, have either not confirmed the obtained results under a controlled environment in the field, or the plants were not grown to maturity. Commonly, the P concentration in such studies has been below a level that is relevant for practical farming. Such low levels would most probably have led to crop failure in the field. My studies indicate that root morphological adaptations to low P concentrations in soil are of theoretical interest, as they demonstrate the ability of plants to survive in contrasting environments. However, for the conditions found in agricultural soil within the Nordic countries, such adaptations probably have little significance.

SAMMENDRAG

I økologisk landbruk er det sterke begrensninger på hvor mye næringsstoffer som kan tilføres gården utenfra, og på skiftenivå blir det lett en negativ næringsbalanse – mer næring fjernes i avling enn det tilføres i gjødsel. Dette gjelder særlig på gårder med lav husdyrtetthet. Undersøkelser på fem gårder i Sør-Norge som hadde drevet økologisk melkeproduksjon med minst mulig fôrinnkjøp siden 1986 eller lenger tilbake, viste at innholdet av fosfor (P) i jorda målt som P-AL (ammonium-acetat laktat løselig) sank over tid, også lang tid etter omlegging. Jo høyere innholdet var ved første gangs måling, jo større var nedgangen beregnet per år. Av til sammen 156 jordprøver fra matjordlaget på de fem gårdene var det bare 6 som hadde lave verdier for P-AL (< 25 mg P kg^{-1} jord) ved andre gangs prøvetaking. Likevel vil det på sikt være behov for tilførsler av P i økologisk landbruk. For kalium (K) var det ikke noen tilsvarende nedgang i K-AL, men for dette næringsstoffet var nivået lavt (< 65 mg K kg^{-1} jord) på en betydelig del av arealet på alle gårdene, og innholdet av tyngre tilgjengelig K var også lavt eller middels høyt. På jord som ikke har en god frigjøring av K fra naturens side vil det derfor bli nødvendig å tilføre K-holdig gjødsel eller jordforbedringsmateriale ved økologisk drift. Det er stort behov for å utvikle næringstilførsler som kan tilfredsstille de kravene som stilles til økologisk produksjon. Videre må man gjøre en enda sterkere innsats for å redusere næringstap fra gården, f eks ved erosjon eller fra husdyrgjødsel, enn det som er vanlig ved konvensjonell drift.

Økologisk landbruk baserer seg på å sirkulere næringsstoffer som finnes på gården. Ved begrenset husdyrhold er det aktuelt å bruke plantemateriale som gjødsel (grønngjødsling, jorddekke). Vi har undersøkt hva som skjer med P, K og nitrogen (N) når opphakket plantemasse ble brukt som jorddekke til grønnsaker (hvitkål, rødbeter). Med en plantemasse tilsvarende ca 1 tonn tørrstoff tilført per dekar økte avlingene med 26%, og ettervirkningen i bygg året etter var 60 kg korn per dekar. Sammenliknet med næringsopptaket i planter uten jorddekke ble lite av næringen i jorddekket tatt opp i grønnsaker.

Opptaket tilsvarte bare 15-20% av N, P og K innholdet i jorddekket. N går lett tapt til luft eller vaskes ut med nedbør, men for P og K ble mesteparten av den overflødige næringa lagret i jorda. Jorddekke-metoden er godt egnet på mindre gårder med lite husdyrhold, der det ikke er kapasitet til å dyrke grønnsaker på hele arealet. Man bruker da ca 2/3 av arealet til produksjon av plantemateriale til gjødsling, og 1/3 til grønnsaker. Det er viktig å ha et systematisk vekstskifte for at ikke næringsstoffene skal bli ujevnt fordelt.

Undersøkelser i svært P-fattige dyrkingsmedier har vist at planter ofte reagerer på lav P-tilgang med å øke rot-skudd forholdet, utvikle lengre og tynnere røtter, lengre rothår og liknende tilpasninger. Planter har en betydelig evne til å tilpasse seg ulike miljø, herunder en varierende næringstilgang. For å undersøke om slike tilpasninger kan være nyttige også i økologiske dyrkingssystem, ble sorter av bygg og vårhvete fra perioden 1900-2000 dyrket i felt med optimal og begrenset næringstilførsel, og i næringsløsning med lavt P-innhold. Sentrale rotegenskaper ble målt i næringsløsning, og i felt med begrenset næringstilførsel. Både næringsopptak og kornavling varierte betydelig, men det var lite samsvar mellom næringsopptak og rotegenskaper hos de ulike sortene. Gjennomgående ga moderne sorter høyere avling enn eldre sorter både ved optimal og begrenset næringstilgang. Viktige årsaker til dette er en høyere kornandel ("harvest index"), og en bedre soppresistens. I kornforedlingsarbeid bør man likevel være oppmerksom på linjenes rotegenskaper, spesielt rotlengden. Mine undersøkelser viste at denne egenskapen kan måles indirekte på en enkel måte, ved hjelp av rotvekten. Det var ingen sikre sortsforskjeller i rotfinhet, også kalt spesifikk rotlengde (antall meter rot per g rot-tørrstoff) verken i bygg eller hvete. Den spesifikke rotlengden er svært arbeidskrevende å måle.

De fleste undersøkelsene som har vist store effekter av et næringsfattig miljø på veksten av røtter eller rothår, har ikke prøvd ut resultatene fra kontrollerte betingelser i felt eller dyrket plantene fram til høsting. I mange tilfeller har P-konsentrasjonen som forsøkene er utført ved vært mye lavere enn det som er mulig i praktisk jordbruk uten å få misvekst. Våre undersøkelser tyder på at rotmorfologiske tilpasninger til lave P-konsentrasjoner kan være viktige for planters evne til å overleve i svært forskjellige miljø. Men i praksis, for de forholdene som gjelder i dyrka jord i Norden, har slike tilpasninger sannsynligvis liten betydning.

CONTENTS

APPENDIX

Papers I-V

The present doctoral thesis is based on the following papers I-V, which will be referred to by their Roman numerals.

I Løes, A. K. and A.F. Øgaard, 2001. Long-term changes in extractable soil phosphorus (P) in organic dairy farming systems. Plant and Soil 237, p 321-332

II Løes, A. K. and A.F. Øgaard, 2003. Concentrations of soil potassium after long-term organic dairy production. Accepted by International Journal of Agricultural Sustainability, vol. 1 (in press)

III Riley, H., A.K. Løes, S. Hansen and S. Dragland, 2003. Yield responses and nutrient utilization with the use of chopped grass and clover material as surface mulches in an organic vegetable growing system. Biological Agriculture and Horticulture 21, p 63-90

IV Løes, A.K. and T.S. Gahoonia. Genetic variation in specific root length in Scandinavian wheat and barley accessions. Submitted to Euphytica International Journal of Plant Breeding.

V Løes, A.K., E.M. Færgestad, T.S. Gahoonia, H. Riley and M. Åssveen. The impact of root traits, nutrient uptake, age of accession, growth period and resistance to fungal disease for cereal production with limited nutrient supply and pesticide use.
Submitted to Crop science

Permission to print Papers I, II and III was kindly granted by Plant and Soil/Kluwer Academic Publishers, The Netherlands, International Journal of Agricultural Sustainability/Channel View Publications, UK and Biological Agriculture and Horticulture/Academic Publishers, UK, respectively.

Background and objectives

This doctor scientiarum thesis has been written to contribute to the further development of organic farming, which in Scandinavia and Germany is often called "ecological" farming. The oldest results included in the study were recorded more than 20 years ago, when organic farming was a rare farming practice in Norway, carried out by idealistic farmers who often practised biodynamic principles. The extent of organic farming practice, described as "alternative" farming, was assessed to 151 farms in 1983, comprising 0.05% of the total farmland (Skøien, 1983). Since then, the number of organic farms has increased to 2303, comprising 3.3% of the farmland in 2002 (Debio, 2003). In 1991, the organic farming method received a legal status by the EU Council Regulation 2092/91 that defines standards for organic plant production. The Norwegian government aims at a 10% fraction of the total farmland being organically managed within 2010 (Ministry of Agriculture, 2003). Organic farming is not any more as exclusive as it once used to be. In a sociological study (Vartdal, 1993), the growth of organic farming was found to have much in common with a classical innovation. Organic farmers could be grouped into innovators, early adopters, early majority, late majority and late-comers. It is reasonable to conclude that at present, organic farmers are comprised of the three categories first mentioned, and that the "early majority" constitutes an increasing proportion. A survey among the 202 Norwegian farmers managing their farm organically in 1992, revealed that food quality, sustainable management of resources, and care for the environment were their main reasons to convert to organic agriculture. However, for 10% of the farmers, increased income was an important reason to convert (Løes, 1992). A governmental subsidy for conversion was introduced in 1990, and premium prices on organic milk in 1995. Hence, most probably the number of farmers that are motivated by a higher income when they decide to convert has increased notably during the last decade. There is a risk that such farmers will go back to conventional farming practice if the premium prices are reduced. To stabilise the further growth of organic farming, and to ensure that the method continues to develop in a sustainable direction, there is a need to strengthen the ideological base of the farming practice. The term sustainability is excellently described in a principal aim of the IFOAM (International Federation of Organic Agricultural Movements) Basic standards, which states that organic production shall ".. support the establishment of an entire production, processing and distribution chain which is both *socially just and ecologically responsible*" (IFOAM 2002; my italics). Such an aim requires a profound understanding of organic production systems, including the interactions of the many factors that constitute them. Knowledge of the management of plant nutrients will contribute to the development of a more sustainable organic agriculture, in addition to the essential agronomic significance of such knowledge. Sustainability is a principal goal of organic agriculture, but conceptual thinking must be followed by practical action. Organic farming has reached an extent where a critical debate of the sustainability of this farming practice is required. The present thesis will contribute in this debate.

The main part of the experimental work presented here was conducted within the framework of a strategic inter-institutional research programme, "Nutrient supply to organic farming systems with small amounts of animal manure" (1998-2002). A former study on farm level was also included, where the initial samples were taken as early as in 1983. The Norwegian Research Council provided funding for both these activities. The first aim of the experimental work was to assess the sustainability of organic farming systems with regard to phosphorus (P) and potassium (K) management. Secondly, I wanted to assess the potential of plant adaptations to low nutrient supply in organic farming systems. Genetic variability in cereal root traits, and the relation between root traits and nutrient uptake by low nutrient supply in the field, was the object of research in this part of the work.

The following questions have been the main topics in the studies included in the thesis:

– What happens with the soil concentrations of P and K after long-term organic management? Is the present management of these nutrient resources in organic farming systems sustainable? (Papers I and II)
– What happens with the surplus P and K that is added to the soil when amounts of chopped plant material required for a satisfactory yield are used as mulch in vegetable growing? Can P and K be redistributed within a stockless organic farming system as chopped plant mulch, with acceptable losses of these nutrients? (Paper III)
– Does the specific rot length (= root fineness) vary significantly among cereal accessions? (Paper IV)
– Can significant genetic variation be found among Norwegian accessions of spring wheat and barley with respect to root traits that are important for the uptake of nutrients in field? (Paper V)
– Are modern accessions of cereals better adapted than older accessions to the growing conditions in organic production systems? (Paper V)

Soil and cycling

Maintenance of soil fertility

In organic farming, a basic principle states that farmers should "maintain and increase long-term fertility and biological activity of soils using locally adapted cultural, biological and mechanical methods *as opposed to reliance on inputs*" (IFOAM 2002; my italics). This statement emphasises that agricultural soil should not be regarded as a passive, inert medium where the nutrients required for plant growth must be purchased and applied. On the contrary, satisfactory soil fertility can be achieved by cycling of the farm nutrient resources. On a line drawn between these contrasting ideas of soil and fertilisation, conventional management is closer to a linear model, whereas organic management is closer to a cycling model (Figure 1).

Soil provides physical support, water and air availability for plant roots, as well as chemical and biological support for plant growth and development. Plant nutrients are released by weathering of minerals, and by mineralisation of organic matter. Recalcitrant soil organic matter has a large impact on soil physical properties, and the soil biota has a significant impact on plant growth. Cultivated soil is tilled and fertilised to ensure satisfactory yield levels. The essential goal of self-sufficiency implies that organic farmers try to minimise all kinds of purchased inputs to the farm. Not only purchased fertilisers, but also fodder and bedding material contain large amounts of nutrients. Due to sale of products, and inevitable internal losses of plant nutrients, the nutrient cycle is not closed, and it may be questioned whether the goal of increased soil fertility can be reached. In Norway, professor emeritus Erling Strand has repeatedly expressed strong criticism of organic farming systems for being non-sustainable because soil reserves of nutrients are reduced (e.g. Strand, 1997, Strand, 1999). Another extreme position is taken by some organic farmers who advocate that fertilisation is not required as long as a satisfactory soil structure is achieved, e.g. by the "Kemmink"-system (Søgaard, 1997; Hansen, 2000). Here, the soil is repeatedly deeply tilled during the growing season, and all machines are driven along fixed lines in the field. There is no doubt that fertiliser demand is increased by poorer soil structure caused by tractor traffic. In a combined fertilisation and soil compaction treatment, amounts of aerated slurry containing 105 kg N, 109 kg K and 17 kg P ha^{-1} y^{-1} was required to achieve the same yields of grass-clover ley with normal tractor traffic, as in the uncompacted and unfertilised treatment (Hansen, 1996). The weathering and mineralisation of nutrients in the soil may be notable, as have been shown in some long-term field experiments referred by Lieblein and Solberg (1996). These authors argue that release of nutrients from the soil may balance the nutrient deficits in organic farming systems. With this hot-tempered debate as a background, changes in soil concentrations of P and K by long-term organic farming were studied to assess if the goal of maintained or increased soil fertility was achieved.

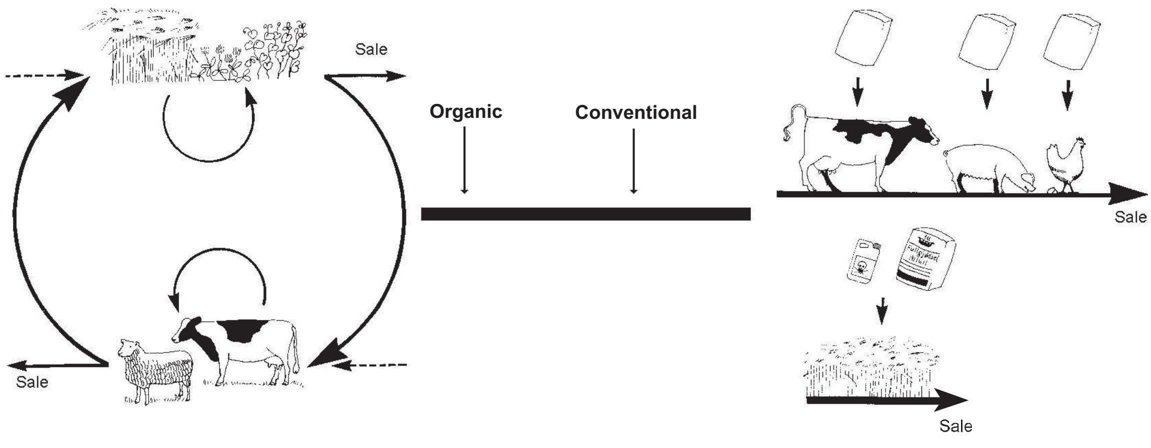

Figure 1. Organic and conventional farming oriented according to contrasting ideas of nutrient management. To the right, the agricultural system is perceived as an industrial unit where required nutrients are purchased to maximise the output for sale, often with a separation of arable and animal husbandry. To the left, the agricultural system is perceived as a cycling of the inherent nutrient resources, where the cycling creates a surplus of outputs for sale. Small amounts of nutrients may be purchased (- - -) when strictly required.

Assessment of soil P and K concentrations by long-term organic farming

In a case study of 12 farms in conversion to organic farming, significant reductions in the soil concentrations of plant-available P and K was found from 1989 to 1995 (Løes and Øgaard, 1997). The inputs of both P and K to the farming systems are reduced during conversion, when purchased fertilisers are gradually omitted and the amount of purchased concentrates and other feed often significantly decreased (Kerner, 1993). Hence, the decreases were not surprising, and we suggested that the levels of available P and K would gradually stabilise on a lower level adapted to the lower nutrient inputs. In stead of waiting several years and sample the same farms again to assess whether this hypothesis was right, we chose five other farms where organic dairy production had occurred for several years to study changes in soil P and K concentrations. Dairy farms were chosen because stockless organic farms are rare in Norway. If the soil nutrient concentrates were found to decrease within these systems, with nutrient budgets being close to zero on the farm level, they may be expected to decrease more rapidly in systems with larger nutrient deficits. In organic animal husbandry systems, the nutrient deficits are usually increased by decreasing livestock density (Eriksen et al., 1995). When manure is legislated for use in organic farming and available for purchase, the farm level nutrient budget may show large surpluses as found for horticultural systems by Watson et al. (2002), but the field level nutrient deficiencies will be very large in stockless systems if no nutrients are purchased.

Soil sampling and analysis

On five dairy farms where a set of initial soil samples was available from the period 1983-1990, a second set of samples was collected from 1996 to 1998. In order to obtain a reliable comparison, the sampling areas (about 80 m^2) were the same on both sampling dates. Both topsoil (0-20 cm) and subsoil (20-40 cm) was sampled, and analysed for ammonium-acetate lactate (AL)-soluble P and K. This extraction method is the common analysis to assess the need for supply of these nutrients in Norway. For P, much more is usually extracted by the AL-method than any crop takes up during one season. Hence, the P-AL extraction reflects soil reserves of P in addition to the immediate P availability from the soil. For potassium, K fractions that are not extracted by the AL-solution also deliver K to crops. Extraction with nitric acid (K-HNO_3) was used to estimate the soil's capacity to deliver K from K reserves. Acid-soluble K is the K extracted by nitric acid minus the K extracted by AL-solution. Farm level nutrient budgets were estimated from annual accounts.

Soil P concentrations

Because of inevitable internal losses (Nolte and Werner, 1994), we have reason to believe that on the field level, averaged over the crop rotation three farms had P deficits (Paper I). One farm had a low surplus, and one had a surplus comparable to conventional dairy farms. On all farms, the average topsoil P-AL concentration decreased from the first to the second sampling (Paper I). The rate of decrease was found to be related to the soil P-AL concentration at the first sampling, so that by a higher initial level, the decrease proceeded more rapidly (Figure 2, steeper lines). The average P-AL level was still medium (26-65 mg P kg^{-1} dry soil) or high (66-150), and only 6 out of 156 topsoil samples had a low P-AL concentration (< 25) at the second sampling. The results indicate that if the farm management is pursued unchanged, the average P-AL value in topsoil will approach a critically low level (Paper I) of ca 30 mg P kg^{-1} dry soil within 15-45 years on four of the five farms (number 1, 2, 4 and 5 in Figure 2). For conventional farming, a P-AL concentration of 70 mg P kg^{-1} soil has been assessed as the best compromise between the aims of high soil fertility and low risk of algae growth due to P pollution of water bodies (Krogstad and Løvstad, 1987). As the N inputs in organic farming is generally lower than in conventional, it is possible that the optimal P-AL level in soil is somewhat lower in organic farming systems. But it may be dangerous to use such speculations as an excuse for depleting soil nutrient reserves. From our study, we concluded that regular records of soil P concentrations are required in organic farming, and that the P inputs should be increased when the average level is approaching the lower part of the medium interval. P inputs applicable in organic farming systems may be increased amounts of purchased fodder, compost from household waste, rock phosphate, bone meal or even human urine (not yet legislated). On the last farm (no 3 in Figure 2), the average topsoil P-AL concentration was 119 mg P kg^{-1} dry soil. The most sustainable way to handle the soil P reserves in such cases is to proceed with negative P balances on field level until a more sustainable level is reached.

In the topsoil on farm 5, that has been managed bio-dynamically since 1932, a larger part of AL-soluble P than is usually found in cultivated soils was organic P (Paper I). Another interesting result was the remarkably even P-AL concentrations in topsoil and subsoil (20-40 cm) on the same farm. This indicates a deep topsoil layer, most probably due to the gentle soil cultivation practice where much tillage has been done by horse, which has resulted in a satisfactory soil structure. This may well have facilitated a large earthworm activity, as has been found by long-term biodynamic farming in farming system comparisons in Switzerland (Pfiffner et al., 1993).

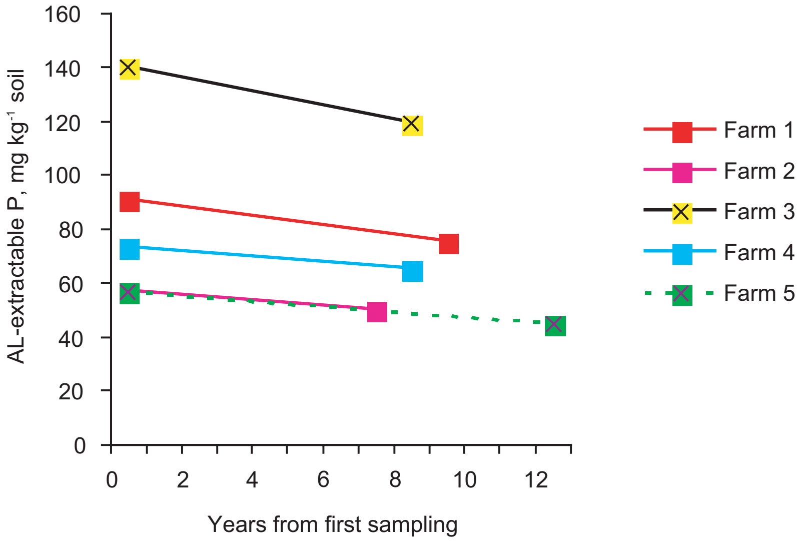

Figure 2. Change in average topsoil (0-20 cm) P-AL concentration on five long-term organic dairy farms during 7-13 years of continued organic management.

Soil K-concentrations

The inevitable internal losses of K are much higher than for P (Nolte and Werner, 1994). Hence, most probably all farms had K-deficits on the field level, averaged over the crop rotation (Paper II). For plant-available K in soil, no significant decreases were found from the first to the second sampling. The average K-AL concentrations in topsoil at the second sampling were medium high (65-155 mg K kg^{-1} dry soil). Between 26% and 45% of the topsoil samples had low K-AL concentrations (< 65), implying that the K availability may be limiting crop production on a significant part of the farmland on all farms if K is not provided in fertilisers or released from soil K reserves (Paper II). With respect to K reserves, the acid-soluble K-concentrations were generally medium to low or low and mineralogical analysis by X-ray diffractometry did not reveal significant amounts of K-releasing minerals. None of the samples studied contained more than 6% illite, and the content of K-feldspars was only 8-13%. Hence, the ability of the soil to replenish K taken up by plants on the farms studied here was generally small. A significant decrease in acid-soluble K was found in both topsoil and subsoil on farm 4, which had a low livestock density and the largest K deficits. As was found for P-AL, the largest decreases occurred on the fields with the highest initial K concentrations on this farm (Paper II).

As was discussed for P, it may be questioned whether the concentration levels indicating "low", "medium" or "high" availability of K are appropriate for organic farming systems, where the N availability is restricted. However, there are not enough data available from organic production to evaluate to which extent the conventional criteria may be used for organic systems. Hence, for pragmatic reasons we have used the well-established conventional criteria. This topic should be further studied.

The K concentrations in soil indicated that there is a serious risk of K deficiency in a significant part of the farmland on each of the farms that were studied (Paper II). Severe K deficiency symptoms have not yet been observed. This does not imply that the yield levels have not been reduced by the K availability. This may be the case in K demanding crops and with dry conditions that decrease the K transport rate in soil both by diffusion and mass flow. A limited K availability in soil may also have a negative impact on the amount of biologically fixed nitrogen (N) in the farming systems. This is because ryegrass is more efficient in the competition for K than red clover (Mengel and Steffens, 1985) and white clover (Salomon, 1999), which are essential legumes in Norwegian organic farming systems. Hence, the farm management should be changed also with respect to K. It is important to consider how all nutrient losses can be minimised. Storage and handling of fodder and manure, as well as the timing of soil tillage and management of crop residues during winter should be considered in this effort. An example is how care is taken of the runoff from platforms where solid manure is composted, and the winter recreation paddocks for cattle. In addition, on farms producing significant amounts of cash crops the crop rotation may be changed. For instance, in stead of K demanding potatoes, grass or legume seed may be cropped. Further, the K inputs to the farming systems may be increased as described for P above.

Sustainability of the P and K management in organic farming systems

Our studies were done on dairy farms with a varying degree of self-sufficiency with regard to nutrients. All farmers aimed at being self-sufficient, but the farmland size was very restricted on two of the farms and some fodder was purchased to ensure a sufficient milk production level. A comparatively larger purchase of fodder is usually linked to a higher animal density, as may be seen from the present study where the size of farmland per milking cow varied from 2.8 to 0.75 ha, and the nutrient deficits were much larger in the first case (Paper II). Our results show that even on organic farms where only milk and some meat was sold, the soil P concentration decreased with time. In self-sufficient farming systems with a significant amount of cash crops, the K concentrations in soil were also reduced.

Do these results confirm the criticism that organic agriculture is non-sustainable? Referring to the IFOAM principles cited above, sustainability implies social justice and ecological responsibility. There is no doubt that the social justice is a strong motivating factor for the farmer aiming at self-sufficiency (Løes, 1992; Vartdal, 1993). A textbook in organic soil cultivation states that "In a global perspective, there is hardly enough resources and energy to introduce industrialised farming practice all over the world" (Hansen and McKinnon 1999, my translation). Mineral P resources are scarce (Lægreid et al., 1999), and with the present use of P fertilisers all known resources will be consumed within 250 years. Hence, mineral phosphates should be used in soils where they would cause significant yield increase, and contribute to reduce hunger problems. Mineral K resources are abundant, both as minerals and in seawater, but the recovery and distribution of mineral K requires energy. With respect to the ecological responsibility on a global scale, the organic farmer takes regard by using local resources and thereby avoiding pollution and energy use during production and transport of mineral fertilisers. By avoiding excess fertilisation, with negative environmental impacts, she is also ecologically responsible on smaller scale. On a farm scale level, to define an ecologically responsible level of soil fertility we may ask at what level the crop production is reasonable in comparison to the required input of energy. Extremely low yield levels as compared to conventional production can not be accepted, but exact minimum yield levels are difficult to set. Criteria to evaluate achieved organic yield levels and to which extent they may be assessed as satisfactory with regard to the input/output ratio of energy and other resources is the aim of a recently started research programme (Eltun, 2002).

When evaluating nutrient management on farm level, a complicating factor is that a possible decrease in soil fertility and yield levels may proceed slowly and for long be masked by yield level variations due to climatic conditions. Analysing whether changes in the farm management are in fact an adaptation to a decreased yield level is also complicated. To decrease farm nutrient deficits, the farmer may increase the amount of purchased fodder, or reduce the number of calves raised for beef production. However, the reason for more fodder may just as well be an increased income, and fewer calves may be due to a demand of reduced work.

From my point of view, there is a risk that strongly motivated organic farmers may over-emphasise the aim of self-sufficiency, reasoned by ecological responsibility on a global level. In consequence, on the local level the farming practice may not be regarded as sustainable in a long-time perspective. Hence, organic farmers have to monitor their soil fertility status regularly, and manage nutrient resources carefully. Organic farming should continue to focus on optimising the use of soil reserves. Some soils have large reserves of P because of a high content of organic matter and/or decades of surplus P fertilisation. Some soils contain minerals that release significant amounts of K. In such cases, negative budgets of P and/or K on field level will be sustainable. Other soils are less fertile with respect to nutrients. In general, there is a need to close the nutrient cycles, so that a larger proportion of the sold nutrients is returned to agriculture. There is an urgent need to study how nutrient sources like human urine and wastes from household and industry can be processed and applied in organic agriculture. It is essential that such products appear in a form that does not compromise soil quality aspects like the content of heavy metals and pesticide residues. However, the EU- as well as national regulations for organic farming systems must be changed to be adapted to a larger degree of nutrient transfer from society to agriculture.

Currently, there is a limited use of mineral K-fertilisers and rock phosphate in organic farming systems, but the amounts that are used are small as compared to conventional systems. Such resources should be regarded as valuable remedies for the least fertile soils assessed on a global scale, rather than being used in excess in wealthy countries. With respect to N, biological fixation will always be the major input in organic farming systems, and it must be emphasised that this discussion is not intended as suggestion to generally legislate the use of mineral fertilisers in organic farming.

Organic plant production with plant material used as nutrient input

So far, organic farming in Norway has mainly been comprised of animal husbandry systems, mostly roughage based productions (dairy, sheep, and beef). The demand for organically produced vegetables and cereals is increasing, and quite a few conventional farmers consider a conversion to organic plant production only if this can be done without establishment of animal husbandry. One possible design of such a system is to produce vegetables for sale one a part of the farmland, whereas the rest is used for production of plant material that is used as nutrient input for the cash crops. Chopped plant material used as mulch combines weed control and nutrient supply for vegetables (Paper III). The method is an alternative way of organising the redistribution of nutrients within a farm, as compared to production of fodder and recycling of nutrients to soil by animal manure. The large amounts of plant material commonly used as mulch to achieve an efficient control of weeds as well as a significant yield increase, implies field level nutrient balances with large P and K surpluses on a small part of the farmland. Up to 3 times the size of the vegetable land must be used for mulch production, dependent on how early in the growing season the first application must be made (Paper III). On this land, there will be a corresponding nutrient deficit. There was a need to study whether the P and K not taken up in vegetables remain in soil, to assess if the mulching system is sustainable with regard to P and K management. By mulching with N-rich plant material, there is a risk of losses of ammonia (NH_3) and nitrous oxide (N_2O), as shown by Larsson et al (1998). This problem should be solved before the method is widespread; however, that was not the task of the present study.

From 1998 to 2001, field experiments were carried out on Norwegian Institute of Crop Science, Research Centre Apelsvoll division Kise (Paper III) to study the effect of chopped plant mulch on yields of vegetables with a varying demand for nutrients, when various amounts and types of plant material were used. The fate of P and K applied in mulch constituted a special study within these experiments.

Vegetables with a different demand for nutrients, red beet with a moderate and white cabbage with a high demand, were grown from 1998 to 2001 on a soil with low to moderate concentrations of P-AL, K-AL and acid-soluble K (K-HNO_3 minus K-AL). Each year, the effect of mulch applications on vegetable yields was studied (Paper III). One or two applications of 9-10 t DM of chopped red clover or grass material per hectare were used. Residual effects on subsequent spring barley crops were measured in 1999-2002. Yield levels and contents of N, P and K in marketable products, crop residues and mulch material, were recorded each year. Residual levels of mineral N in the soil were measured each year after harvest. Soil concentrations of P and K were measured preliminarily in 1998 and in more detail in 1999. The mulch treatments tested each year were modified, according to experience gained in the previous year. At harvest, the weights of marketable products and crop residues were recorded and samples of both were taken for analysis of DM content and N-, P- and K-concentrations. Only the marketable products were removed from the field. Leaves and stems were incorporated into the soil by rotovating soon after harvest, and the plots were ploughed in the following spring.

The nutrient management was evaluated by apparent recovery of nutrients, which is the amount of N, P or K in above ground plant material in treatments receiving no mulch (control crop) subtracted from the amounts in treatments receiving mulch. The recovery was expressed as a percentage of the amount applied. The recovery may be underestimated if the control crop takes up more nutrients from soil that the mulched crop. On the other hand, there is also a risk that the recovery is overestimated, because the mulched crop in fact takes up more nutrients from the soil than the control crop, because the mulched crop grows faster. However, not subtracting the nutrients taken up in the control crop would imply that all nutrients in mulched crops originated from the mulch, which is obviously not the case. It must be kept in mind that the apparent recovery will be influenced by the soil fertility. In fertile soil, the apparent recoveries will be relatively larger due to a higher nutrient uptake in the control crop.

Effect on yields of vegetables and subsequent barley, and the recovery of mulch N, P and K

One mulch application of about 10 tonne of dry matter (DM) ha^{-1} increased the yields of both crops significantly. On average, the saleable yields were increased from 27 to 33 tonne fresh weight (FW) ha^{-1} of red beet, and from 44 to 56 tonne of white cabbage. For conventional farming in this district, 30-40 tonne of red beet and 60-80 tonne of cabbage per hectare are typical yields, so the mean yield levels obtained with mulch seem satisfactory. However, the average apparent recoveries of mulch derived nutrients in aboveground plant parts were only 13%, 14% and 18% of N, P and K, respectively, as was reflected by large amounts of surplus P and K in the nutrient budgets shown in Table 1. Some 3-10% of the N supplied in mulch was found as mineral N at 0-60 cm soil depth after harvest, and subsequent barley yields were increased by on average 620 kg ha^{-1}, or 20%. In spite of the effect on subsequent cereals, the low N use efficiency indicates that much N was lost by NH_3 volatilisation, or by denitrification. Such nutrient losses represent a serious challenge for organic farming systems, aiming at being environmentally friendly. It should not be accepted that harmless N_2 is biologically fixed to plant protein, and later transferred to gases that are harmful with respect to climate change (N_2O) or nutrient enrichment of the atmosphere and precipitation (NH_3). Efforts must be taken to increase the utilisation of biologically fixated N within organic farming systems.

The yield increases varied much from year to year (Paper III). By the lowest yield level that was obtained in the control treatment, 34 tonne ha^{-1} of white cabbage (experimental year 2000), the yield increased to 42 tonne ha^{-1} by one application of chopped clover material. By the highest yield level that was achieved, in 2001, the cabbage yield increase was from 52 to 64 tonne ha^{-1}. A large variation in yield levels without mulch application was to be expected, because the yields are then dependent on the release of nutrients by mineralisation of organic matter and weathering of soil minerals. Both these processes are influenced by the weather conditions. It might have been expected that fertilisation by mulch application would stabilise the yield levels, but on the contrary, the yield increase was proportional to the control yield level, so that the effect of mulch was largest in the years when the yield level was generally highest. This result probably reflects that the N availability from mulch is at least as variable as is the soil N-mineralisation. The developmental stage of the plants used for mulching also has a large impact on the rate of decomposition. The recovery of nutrients was greatest in the case of mulch material that was broken down slowly, but still had a comparatively high concentration of N (cocksfoot; *Dactylis glomerata L.*).

Nutrient budgets reflected in changes in soil P and K concentrations

Without mulch application, there was no statistically significant change in the topsoil P- or K-concentrations from spring to late autumn (Table 5, Paper III). For comparison with the surplus amounts of P and K applied in mulch, the concentrations have been expressed on an area basis, multiplying the concentrations by the soil volume and an average bulk density of 1.45 kg dm^{-3} after correcting for an average gravel content of 15%. In mulched treatments, the increase in topsoil P-AL amounted to 25 kg P ha^{-1} in red beet and 15 in white cabbage, which is somewhat less than half of the surplus P applied in mulch (Table 1). With the larger surplus in red beet, the fraction of P that could be accounted for as soil P-AL was slightly larger, 41% as compared to 34% in cabbage. It was interesting to see that the P taken up in saleable products in the control treatments without mulch did not cause significant decreases in the soil P-AL concentrations. This indicates that soil P-AL was replenished during the growing season.

For K, the increases in topsoil K-AL and acid-soluble K were slightly larger than the surplus added in mulch. The K-AL increases corresponded to 209 kg K ha^{-1} in red beet and 174 in cabbage, and the acid-soluble K increases to 252 kg K ha^{-1} in red beet and 199 in cabbage. Hence, the total increase in extracted soil K (K-AL plus acid-soluble K) was larger than the K surplus for both crops. The amount of K not accounted for amounted to 139 kg K ha^{-1} for red beet and 81 for cabbage. The amounts of K taken up by plants in the control plot (Table 1) were considerably larger than the decreases in extracted soil K in these plots, which amounted to 40 kg K ha^{-1} for red beet and 87 for cabbage. Hence, the experimental soil had a capacity to replenish some of the

Table 1. Field level nutrient budget for P and K (kg ha^{-1}) by two mulch applications to vegetables in 1999. P and K removed is the uptake of nutrients in plant parts removed from the field.

	Red beet		White cabbage	
	No mulch	Two mulches	No mulch	Two mulches
P BUDGET				
P in mulch	0	71	0	71
P removed	8	10	19	27
Surplus of P	-8	61	-19	44
K BUDGET				
K in mulch	0	490	0	490
K removed	90	168	135	198
Surplus of K	-90	322	-135	292

K taken up by plants. In part, the unexpectedly high soil K-concentrations in autumn in the mulch treatments may be due to analytical inaccuracy, but it may also be questioned if the mulching has stimulated soil biological processes and thereby a transformation of mineral K to K extractable with AL-solution or nitric acid.

In the subsoil, no changes in P or K concentrations were found during the season. As the subsoil layer measured here was rather thick (25-60 cm), the P-AL values varied more at this depth than in the topsoil, and because the surplus of P was low as compared to that of K, possible increases in subsoil P concentrations may have been obscured. However, the unchanged subsoil K values suggest that there was probably no transport of this nutrient from topsoil, and as K is more mobile in soil than P, this indicates that the nutrients applied in mulch were stored in the topsoil. The surplus P that could not be accounted for as P-AL may have been bound in soil faunal biomass (and hence was not extracted by AL-solution), or it may have been adsorbed to soil minerals in a form not extractable by AL-solution. The surplus required to increase the P-AL concentration by 1 mg kg^{-1} of topsoil, was 7.6 kg for red beet and 11 for cabbage. These values correspond well with values found by Øgaard (1995) in a long-term experiment with mineral P-fertiliser in a soil with an initial P-AL value of 50 mg P kg^{-1}. In that study, a surplus of 6.5 kg P ha^{-1} increased the P-AL concentration by 1 mg kg^{-1} topsoil (0-20 cm). For a 25 cm layer, the amount of P surplus required to increase P-AL by 1 mg would have been approximately 8 kg, which is comparable to the results found in the present study.

Sustainability of the P and K management by chopped plant mulch vegetable growing

The main arguments in the disfavour of using plant material as a fertiliser are a low recovery of nutrients, as well as the negative environmental impacts of the gaseous N-losses. If the P and K not recovered in crop yields are lost to water bodies, the P may increase algae growth and both P and K losses will reduce the soil fertility of the farming system. However, losses of P and K may not be very likely. No indications of losses were found in the present study. It is possible that losses may occur on light textured soils with less ability to absorb excess nutrients, especially by higher levels of soil P and K concentrations than was found in the present study. However, in general the mulch will prevent soil erosion and runoff both directly because of the soil cover and indirectly because of a better soil structure and increased infiltration rate. Hence, it is possible that P and K losses may be reduced as compared to bare soil. The mulch application will increase the fertility of the field(s) used for vegetables, as was shown by the significant increases in subsequent cereal yields (Paper III). If large areas are available that are well suited for mulch production because there is no better alternative use of that land (e.g. former pasture), the mulch system may be an analogue to the former farming systems based on nutrient import from outlying fields. The system may be of interest for farmers where the farmland size is relatively large in comparison to the amount of work that is available per growing season. Cultivated land has to be cropped each year, and selling roughage is not an alternative for organic plant production systems because this would cause too large nutrient deficits. Producing nutrient inputs for redistribution within the farm requires little labour and investments as compared to establishing an animal husbandry production.

The gaseous losses of N from vegetable manure may be reduced by a dressing of soil (Janzen & McGinn, 1991) or chopped wood (Larsson, 1997). Such amendments require extra work, and a soil dressing will decrease the weed control effect of the mulch. Nevertheless, possibilities of decreasing gaseous N-losses should be further studied. They warrant special attention since organic farming aims to be environmentally sound. Amendments that increase the N recovery from chopped plant mulch may also be used to increase the recovery from other green manure plants. In conclusion, if the utilisation efficiency for N can be increased, the chopped plant material mulch system seems to be a sustainable method to redistribute plant nutrients, ensure an agronomically sound crop rotation and produce cash crops within stockless organic farming.

Plant adaptations to limited P and K availability in soil

When searching the web for the term "plant adaptations", 58 858 pages were found. On of these, from The Missouri Botanical Garden, explained the meaning of plant adaptations as *The special characteristics that enable plants and animals to be successful in a particular environment*. Plant adaptations to extreme climatic conditions, calcifuge and acidifuge plants and adaptation to high salt concentrations in soil were described; all of which may be studied in wild species as a part of the general botany. However, crop plant adaptations to low nutrient concentrations in soil remains a topic of agronomic interest. Many studies are published within this field, including such various topics as the impact of mycorrhiza, root exudations and uptake mechanisms at the cell level. In this thesis I have focussed on traits related to root morphology. No other adaptations to limited nutrient concentrations will be discussed; however, an overview has been provided in Løes (1999). The presentation is restricted to spring wheat and barley, which are important crops in organic farming systems in Northern Europe.

The interest of plant adaptations in organic farming systems

Yield reductions in organic production due to limitations in nutrient supply

Because of the aim of self-sufficiency, and restrictions posed on purchase of nutrients, the nutrient supply is generally limited in organic farming systems as compared to in conventional farming. In a Danish study comparing 36 pairs of organic/conventional mixed dairy farms, the use of fertilisers and manure was considerably higher on the conventional farms (Halberg and Kristensen, 1997). On average 31 tonne of animal manure plus 148 kg N ha^{-1} y^{-1} was applied on a conventional field, as compared to 21 tonne of animal manure ha^{-1} y^{-1} on an organic. Most probably, some of the conventional fertiliser was compound and hence increased the input of P and K in the conventional system. The yield level was 21-37% lower in organically produced cereals and 12-18% lower in fodder beets and grass-clover crops. Nutrient availability was suggested as an important reason for these differences. Comparable yield level differences were found in Norwegian studies (Kerner, 1994; Ebbesvik, 1997), and a positive relation was found between organic ley yields and the amount of N applied in manure. In a farming systems comparison study, the organic cereal yields were 60% of the conventional, on average for 2000-2002, 3.33 t ha^{-1} y^{-1} (Korsæth et al, 2003). No nutrients except from biologically fixed N were applied to the organic system, whereas in the conventional plant production treatment, 31 kg P, 88 kg K and 123 kg N ha^{-1} y^{-1} were applied in mineral fertiliser on average for the four-year crop rotation (Korsæth et al., 2001). These results demonstrate that in both mixed animal and cash crop organic farming systems, plant growth is restricted as compared to in conventional systems, and that one important reason for the yield difference is the nutrient availability.

Because of the lower level of P and K inputs to organic farming systems, such systems will be relatively more dependent on the soil's ability to release phosphate and potassium ions by mineralisation of organic matter and weathering of minerals. These processes may be stimulated by a relatively better soil structure (Mäder et al., 2002) and a higher biological activity in soil (Oberson et al., 1996) in organic farming systems. However, in general the plant growth will relatively often be limited by the nutrient supply in organic farming systems as compared to conventional.

Plant growth retardation by nutrient deficiency

During vegetative growth there is a large demand for N in meristematic tissues where cell division occurs, because of synthesis of proteins and nucleic acids. Hence, the extent of vegetative plant growth is largely determined by N-availability (Mengel and Kirkby, 2001). By limited N-availability, the initial response will be a decreased leaf elongation rate (Sinclair and Vadez, 2002). Photosynthate will be accumulated as starch and fructans in leaves and stems whereas the protein content will be depressed. The same processes will occur in the plant if P or K availability is retarding the vegetative growth (Mengel and Kirkby, 2001). P is essential for the synthesis of nucleic acids, and K acts both as a stimulator of plant enzymes and a regulator of osmotic pressure, which is important during cell elongation. As a consequence, plant growth may be significantly reduced because of unbalanced or generally limited nutrient availability without that any symptoms of nutrient deficiency can be observed. This retardation in plant growth may be seen as a primary plant adaptation to limited availability of P and K.

Which macronutrient that limits growth in organic farming systems will vary according to the crop as well as to local soil and climatic conditions. When N-mineralisation and biological N-fixation is high, the availability of P or K may become the limiting factor of growth. However, in a Nordic climate, both N-mineralisation and fixation will commonly be restricted by climatic con ditions. A significantly lower rate of N-fixation was found in red clover grown in Northern Norway as compared to the southern part of the country; 128 as compared to 210 kg N ha^{-1} y^{-1}, respectively (Nesheim and Øyen, 1994). Hence, it is well possible that N-availability is limiting plant growth in Norwegian organic farming systems to a larger extent than in countries with a more favourable climate. There may be a potential to increase the biological N-fixation, e.g. by more efficient Rhizobium strains, or crop cultivars adapted to cold climate. A variety of lucerne with higher N-fixation capacity has been released (Barnes et al., 1988; referred in Sinclair and Valdez, 2002). Recycling of human urine may also have a large potential to reduce N-deficiencies in future organic farming. Hence, plant adaptations to limited P and K availability in soil are of interest in organic farming systems in spite of that N may often be the most limiting nutrient.

Root morphological traits increasing the nutrient uptake

Root architecture is of major importance for plant nutrient uptake. By increased root density in soil, a larger interface between soil minerals, organic matter particles and plant roots is developed. By deeper rooting, a larger soil volume will be exploited. Root hairs enhance the nutrient-absorbing surface of the root manifold. A relatively large root mass, with relatively thin roots that spread their way through a large soil volume, would be a useful plant adaptation to limited nutrient availability. This may be achieved by allocation of a relatively larger amount of photosynthate to root growth. The root DM/shoot DM ratio has been widely used as a measurement of this allocation. Alternatively, the root length per g total or above ground plant matter may be used (Nielsen, 1983), commonly abbreviated L*. This trait is less dependent on the developmental stage of the plant than the root/shoot ratio. With respect to spring wheat and barley, significant genetic variability in root length, rooting density and root hair length (RHL) has been found in many former studies, referred in Paper IV and V.

Studies of the specific root length

In less fertile soil, where the subsoil also contains nutrients, a high root density is essential for the nutrient uptake and the root length is probably the most important root trait with such conditions. Measuring the root length requires much work, and hence is often avoided in cereal breeding. However, the specific root length (SRL, m g^{-1} root DM) did not vary significantly among the cereal accessions studied in this thesis (Paper IV). As shown in Figure 3, the root length is closely related to the root weight. Hence, root lengths can be estimated with sufficient reliability by the root weight and an appropriate SRL value. It should be observed that this value will be lower for roots grown in soil as compared to roots from hydroponics (Paper IV), because some soil particles will stick to the root surface even after cleaning. Calculating the root length instead of measuring it, may facilitate further root studies in cereals.

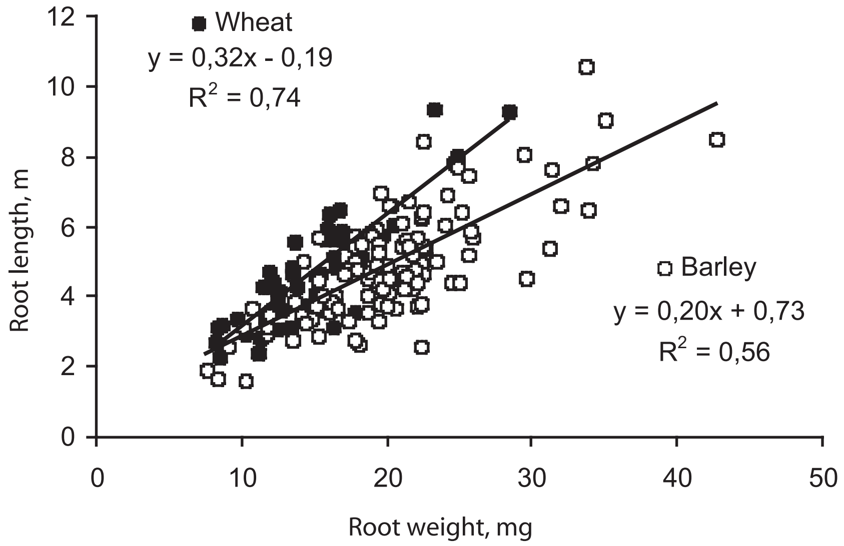

Figure 3. **Relation between dry weight and length of scanned root samples of 17 wheat and 35 barley accessions grown in nutrient solution with sub-optimal P availability.**

Relations between root traits and nutrient uptake in field for selected Norwegian accessions of spring wheat and barley

A study of winter wheat cultivars released in the period 1969-1988 (Foulkes et al., 1998) showed that the oldest of these cultivars had a relatively higher ability to take up N from soil without N supply. Opposite to this, the most recent cultivars had a relatively higher uptake of N applied in fertiliser. This demonstrates that cereal cultivars may in fact gradually become adapted to higher levels of fertilisers, and possibility exists that this may hamper root traits essential for nutrient uptake from less fertile soils. To avoid such adaptations, the selections of cereal cultivars in field should be done with modest supplies of nutrients to the soil.

As root traits are especially tedious to measure in the field, screening of root traits with controlled conditions in nutrient solution could simplify the breeding of nutrient efficient cultivars. Bertholdsson (2000) found a close relation between seminal root length and nutrient efficiency in field when growing seedlings in hydroponics with oxygen stress. On this background, we decided to test whether genetic variation in some root morphological traits of importance for nutrient uptake could be found in Norwegian accessions of spring wheat and barley. Further, we wanted to study if such differences measured in controlled environment could be verified by studies of nutrient uptake and grain yield in the field.

Experimental design

52 accessions of spring wheat and barley were selected to represent the cultivars bred and grown in Norway during the period 1900-2000. Two Norwegian wheat accessions, and five Swedish barley accessions selected for organic farming were included. On the basis of root traits recorded in circulation low-P nutrient solution, 20 accessions (9 of wheat and 11 of barley) were chosen for comparing nutrient uptake and grain yields in field by limited nutrient supply and pesticide use. The accessions with maximum or minimum values for L* or RHL in nutrient solution were chosen, to be able to reveal differences in the field. The selection of 20 accessions included old land races and accessions released in the middle of the century, but the proportion of not yet released accessions was larger than it was in the selection of 52 accessions. The above ground DM (ADM) and uptake of N, P and K was recorded at 2 weeks interval from 18 June to 16 August, and by the final harvest in early September. As all the 52 accessions were grown by optimal nutrient supply prior to the nutrient solution experiment, grain yields could be compared by different nutrient supply. Further details on cereal accessions, nutrient supply, chemical analyses etc. are shown in Papers IV and V.

Root traits as related to nutrient uptake in the field

Significant genetic variation in L* was found in barley, but not in wheat (Paper V). For both cereal species, significant genetic variation was found in RHL both in nutrient solution and field by low nutrient supply. However, there was no close relationship between L*, RHL in nutrient solution or RHL in field, and the nutrient uptake in field. The nutrient uptake in ADM during the growing season varied significantly between accessions, but the accessions that most often had the highest uptake of N, P and K were not the same accessions that produced the highest grain yield at the final harvest. At each sampling, the uptake of N, P and K in ADM were closely related.

Grain yield levels and the usefulness of modern accessions in organic farming systems

By optimal supply, barley produced higher grain yields than wheat, on average 5.6 as compared to 4.6 t ha^{-1}. By limited supply, the average wheat and barley yields were comparable; 3.6 and 3.8 t ha^{-1}, respectively. The ranking between accessions with respect to grain yield was comparable with optimal and limited nutrient supply. The highest grain yields were achieved by modern accessions that were fairly resistant to the dominating fungal diseases. In wheat, this was mildew (*Blumeria graminis* (Oudem.) J.J. Davis), and in barley, it was scald (*Rhynchosporium secalis* (Oudem.) J.J.Davis). A higher harvest index contributed notably to the increased grain yields for modern accessions. Modern accessions, especially lines selected for organic farming, performed best of the accessions studied here. However, some older accessions possessed interesting traits e.g. resistance to mildew (wheat cv. Snøgg), or a high nutrient uptake during the season (wheat cv. Møystad, barley cv. Lise) that may be useful in further breeding. The study indicates that in Norwegian accessions of spring wheat and barley, genetic differences in nutrient uptake are present, however, these differences will be of little significance for the grain yields that can be achieved in organic farming systems as compared to other factors.

The relevance of low-P studies in controlled environment for organic farming systems

Several studies have shown that plants respond to a decreased nutrient availability by producing relatively more roots. The root/shoot ratio was found to increase for different plant species by reduced P-availability, especially in wheat and ryegrass (Föhse et al., 1988). In a laboratory experiment comparing barley varieties, Römer and Schenk (1998) found longer roots by low P-conditions, on average 40 m roots per plant, as compared to 25 m by optimum P-fertilisation. In the same study, the root mass increased from on average 112 mg DM per plant for optimum P conditions, to 165 mg by low P, after 20 days of growth in a climate chamber (Schenk, 1992). The average total plant mass was equal, 412 mg DM per plant by both P levels. This indicates that the plants invested relatively more of their dry matter production in root growth by low P-availability.

However, these results do not imply that by a relatively lower nutrient concentration in field, the root mass will generally increase. As described above, the general response to deficiency in macronutrients is decreased growth. Mollier and Pellerin (1999) found a large and rapid decrease in leaf expansion in maize when establishing P deficiency. After a temporary short-term increase, the root growth was also significantly decreased. The explanation was that with the rapid decrease in leaf expansion, excess carbohydrates were for a while available for increased root growth. Thereafter, with reduced leaf area the amount of carbohydrates fixated by photosynthesis decreased, causing a significant decrease in root growth. This study supports the view that with decreased nutrient supply, the total amount of plant material and thereby also the root mass will decrease. For wheat and barley accessions grown in field with different P-concentrations in soil achieved by long-term differences in P application (Holten, 2002), the average ADM increased with increasing soil P-concentrations up to the second highest level, where it flared (Table 2). This result was to be expected. The root mass, which was recorded indirectly by measurement of root in-growth in buried soil bags, increased by increasing P-concentrations, even to a larger extent than the ADM production (Table 2). This is contradictory to the results of Föhse et al. (1988) as well as Schenk (1992). The reason for the disagreement is probably different soil P-concentrations. In the subsoil used by Schenk (1992), the initial concentration corresponded[1] to < 5 mg P-AL kg^{-1}soil. It was enriched with 13.6 mg P kg^{-1} in the low P treatment and 136 mg in the optimum P treatment, and hence the P-availability was probably more limiting in the low-P treatment of Schenk (1992) than in the study of Holten (2002), see Table 2. In the subsoil used by Föhse et al. (1988), the P-CAL concentration "transformed" to P-AL[1] varied from 6.5 to 82 mg P kg^{-1} soil for the levels where shoot DM increased with P fertilisation. It was especially from the concentration levels corresponding to P-AL= 6.5 to P-AL = 23 that the root/shoot ratios were found to decrease significantly, whereas from P-AL =23 to P-AL = 82, the ratio decreased only slightly for wheat and was in fact increased for ryegrass (Föhse et al. 1988). For a Carex-species, Powell (1974) found a constant root/shoot ratio by increasing soil P-concentrations from a value corresponding to 19 mg P-AL kg^{-1} soil, to a value of 116 (Figure 4).

Table 2. Average values of aboveground dry matter (ADM) yields in mid-July for two accessions of spring wheat and four of barley, and DM of in-growth of roots (IGR) relative to ADM per m^2. Data recorded at ear emergence/anthesis growth stage. (Holten, 2002)

P-application[2]	**Soil P-AL**	**ADM**	**IGR DM/ADM**
kg ha^{-1} y^{-1}	mg P-AL kg^{-1} soil	g m^{-2}	g * 1000 per g
0	35	354	0.26
16	49	476	0.37
32	87	604	0.40
48	130	587	0.51

[1)] The soil P-concentration (Schenk 1992) was < 10 mg P_2O_5 extracted by calcium-acetate-lactate (CAL). According to Sibbesen and Sharpley (1997), one unit of CAL-soluble P corresponds to 1.8 units of P-AL, whereas one unit of Olsen-P corresponds to 3.2 units of P-AL

[2)] Applied each year since 1966

Low P-concentrations in soil have also been found to cause relatively longer root hairs in cereals (Gahoonia et al., 1999). Pictures showing diminishing root hair lengths in a soil with P-concentration corresponding to 149 mg P-AL kg^{-1} soil, whereas with 45 mg P-AL kg^{-1} the root hairs thrived, contribute to the impression that plants compensate lower P-concentrations in soil by increasing root or root hair growth. However, for the cereal accessions studied by Holten (2002), the root hairs were significantly longer with 87 as compared to 35 mg P-AL kg^{-1} soil; on average for barley, 0.93 as compared to 0.83 mm, respectively. This result is in line with the fact that decreased nutrient supply causes a general reduction in growth.

In conclusion, the detailed experimental studies of plant adaptations to low nutrient concentrations in soil or hydroponics must be interpreted with much care when used to generalise knowledge about plant growth in field. Increased root growth or similar responses to decreased nutrient concentrations should not be regarded as if such plant adaptations may have a significant impact in organic farming systems with limited nutrient supply. However, this somewhat negative conclusion should not be seen as a contradiction with acknowledging the importance of a satisfactory soil structure and a high root density in all the fertile soil depths in organic farming. As mentioned in the introduction, these factors are essential for organic crop production.

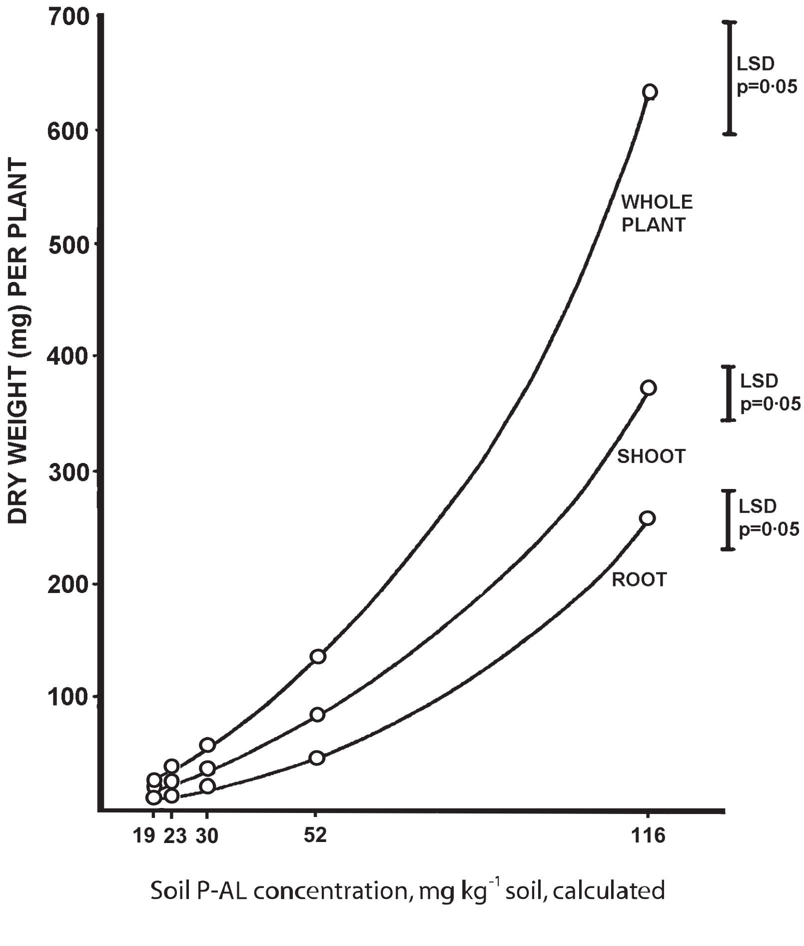

Figure 4. Growth of root, shoot and the whole plant of *Carex coriacea* at soil P-concentrations corresponding to 19, 23, 30, 52 and 116 mg P-AL kg^{-1} soil, assuming that the bulk density of the silt loam used in the pot experiment was 1 kg dm^{-3} soil. Adapted from Powell (1974).

Acknowledgements and personal comments

The aim of the present thesis was to assess the sustainability of organic farming systems with regard to soil P- and K-concentrations, and to study some plant adaptations to low nutrient concentrations. The close relation between a growing crop plant and the soil surrounding its roots has been a fascinating object for agronomy researchers for centuries, and the relevant literature is too extensive for a single person to digest. Even so, much is still obscure about how plants acquire the nutrients they need to grow and develop. At the start of the work, I thought that after doing it, I would know this. Now, approaching the end of the work, I realise that I still do not know really what happens when the nutrients change their state of condition from being a part of the soil, to being a part of the plant. However, I have learned how complicated it is, how many processes that are involved, and how many possibilities exist for plant adaptation to conditions of suboptimal nutrient availability. Out of this multiplicity, I have focussed on root morphological characteristics, which comprised working with pictures that contained much qualitative information in addition to the numbers that could be derived.

As the planning of the strategic programme started early in 1997, I devoted a period of more than 6 years to produce this thesis. During this period, my small children turned into teen-agers, and my family, used to living on a shore with rabbits in the garden, experienced that survival was also well possible in a large city like Copenhagen. This big adventure in our lives happened when I stayed one year at the Plant nutrition and soil fertility laboratory in the Department of agricultural sciences at the Royal veterinary and agricultural university in Denmark. The Copenhagen period was very instructive and fruitful also from a scientific point of view.

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